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On the Action of Electric Current on Fishes II.

Electrophobotaxis of Fishes in a Group.

By

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(Received June 12th, 1929).

It is a well-known fact that when fishes enter a field of electric current they feel the current and under a certain condition try to escape from the field. The aim of the present study is to make a statistical investigation on the efficiency of several fields of electric current in suspending the movement of a fish-group specially when swimming up stream.

Method of Experiment. A wide wooden conduit with an artificial stream fed by an artificial water-fall at one end and flowing down at another with a controllable speed was used. At the beginning of the experiment, the area of the conduit was $0.6^{m} \times 3.5^{m}$; it was enlarged to $0.9^{m} \times 3.5^{m}$, and finally to $0.9^{m} \times 5.0^{m}$. The depth of water was almost unaltered, namely, $9^{cm} \sim 10^{cm}$. Electrodes used ware made of similar rectangular plane gratings, each having vertical or horizontal meshes of equidistant parallel wires, about 1.2^{mm} or 1.6^{mm} in diameter. Facing upstream, an odd number of such electrodes reaching to the bottom were arranged one behind another and were supported in parallel vertical planes at right angles to the direction of water flow, as shown in Fig. 1. Each set of every other electrodes was connected with each secondary terminal of a transformer supplied with 100 volt alternating current of 50 cycles on its primary terminals. Such an arrangement of electrodes makes the current flow mostly in the direction along which a fish-group enters the field of electric current; and it was experimentally ascertained[1] that the necessary potential-gradient to be felt by a fish is less

(1) OKADA, M.: On the Action of Electric Current on Fishes I. Excitation and Narcosis. J. Imp. Fish. Inst. XXIV, 2, P. 64, 1929.

when it is swimming into the electric field along the stream lines than along equipotential lines. Recently it was reported that such a field was most effective to prevent fish-groups to pass through.(1) The intensity of field of current was so made that the further a fish-group goes up stream, the stronger current it may meet with, because such a field has been proved very effective.(2) This was obtained either increasing the spacing between the electrodes one by one, or lowering the voltages with resistances step by step in the foreparts of the field, as shown in Fig. 1.

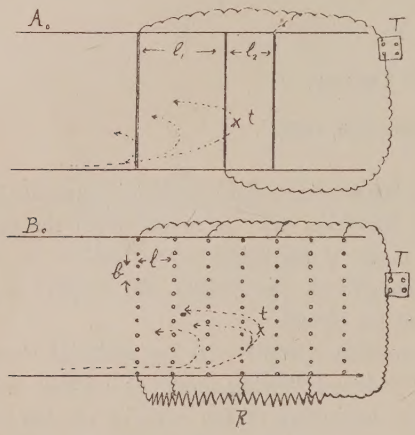

Fig. 1.

T: transformer, *R*: resistance, *t*: turning point.

While the condition of the electric current was kept unchanged, the efficiency of the field was tested in the following manner :— 30 ~ 50 *Cyprinus carpio* L., having body length about 4~7cm, were taken out of 200~300, and put in the artificial stream. When a fish-group, swimming up steam, entered the field of electric current fishes in the group turned back after going a certain distance through the electrodes. Among those points at which any fish turned his course, the farthest one from the frontest grating was sketched, and about 30 similar cases were repeated. For the sake of convenience, I propose to call the position thus sketched the *turning point* of the group. The *turning points* were also tested in the case where the electrodes were not supplied with electric current and it was ascertained that, in such a case, almost all groups passed through the whole system of electrodes. Every different field of electric current was tested in the similar way.

Experimental Results. From the records of distribution of *turning points* the following results were obtained.

(1) McMILLAN, F. O.: Electric Fish Screen. Bulletin of the Bureau of Fisheries XLIV. Document No. 1042. p. 97, 1928.

(2) OHTA, T.: Investigations on Electric Current and Living Fish. Suisan Kenkiushi XIX, 12, P. 15, 1924 (in Japanese). OKADA, M.: A Note on Leading the Movement of Fish Groups by Electric Current. J. Imp. Fish. Inst. XXIV, 5, p. 124, 1929.

1. Rate of the number of groups prevented in their course in relation to the intensity of electric current: When the spacing between the ith and $(i+1)$th electrodes, l_i, is greater than about $2 \times \frac{2}{3}$ [(1)] times of the breadth of a mesh of grating, b, the intensity of the current in the middle part between those electrodes, v_i, is practically uniform and is proportional to the voltage on those electrodes, V_i. Let the number of *turning points* which lie before the $(i+1)$th electrode be N_i in the total number N, and put $r_i = \frac{N_i}{N}$, then the relation between r_i's and v_i's or V_i's are found, for example, to be as represented in the graphs in Fig. 2. (1)~(4).

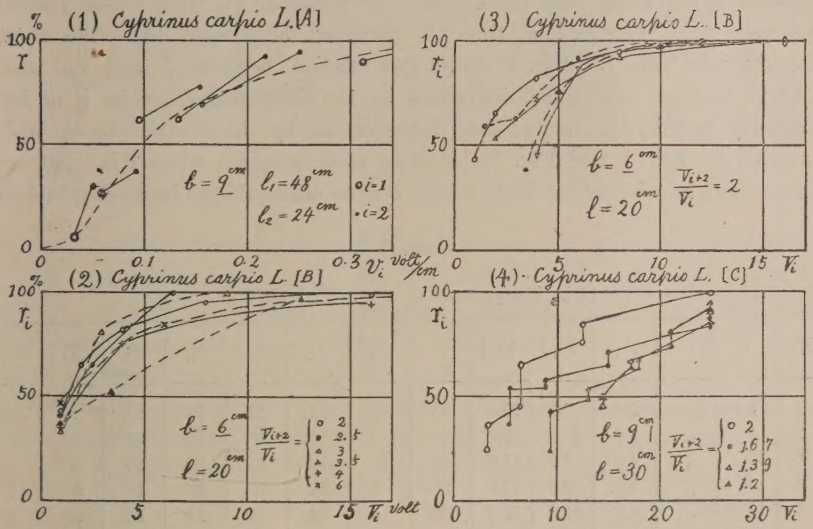

Fig. 2.

Examples showing the relation between the rate of number of groups prevented from passing through the $(i+1)$th electrode, r_i, and the intensity of current, v_i or V_i. The marks connected by each line were obtained in the same test at the same time. In (1), (2) and (3), the electrodes had horizontal meshes, and in (4), the vertical. Arrangement of electrodes was, in (1), as shown in Fig. 1. A. and in (2), (3) and (4), as shown in Fig. 1. B. In this figure, [A], [B] and [C] denote the fishes in different stock.

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(1) F. O. McMillan says that the spacing between rows of pipe electrodes should be approximately 1,33 times the spacing of the electrodes in the rows. l.c. P. 123.

In the case of Fig. 2. (1) the marks representing the relation just stated above lie nearly on one smooth curve, while in the others they are more or less scattered or there are seen a systematic shifting between the curves of different tests.

2. Rate of number of groups prevented in their course in relation to the spacing between electrodes and breadth of meshes: In the equidistant arrangement of electrodes as shown in Fig. 1. B, the relation between r_i and the spacing of electrodes, l, or the breadth of meshes, b, was investigated. In the first place, the breadth of meshes, b, only was changed, while the voltages between each pair of electrodes were so adjusted that $v_i's$ were remaining almost unchanged (5); and in the second place, both l and b were changed in the same proportion, when the voltages, V_i, were changed also in the same proportion as l, so that $v_i's$ remained unchanged (6). The results are given in Tab. I. Fig. 3 shows the relation between b and r_i, which tells us that r_i is not much influenced by the difference either in b or in l. Contrary to this, the rate of dead fishes caused by the electric shock, which is given in Tab. I and Fig. 3, increases as b increases, when l is kept constant. In the case where both b and l were changed, the increasing in death

TABLE I.

(5) *Cyprinus carpio* [C]. Temperature of water=17.6~18.4°C.

No.	b	l	$V_{1,2}$	$V_{3,4}$	$V_{5,6}$	N	N_1	N_2	N_3	N_4	N_5	N_6	Dead
			volt	volt	volt								
1	6cm	40cm	2.8	8.6	25.0	30	8	11	12	16	28	30	0
2	9	„	3.6	10.9	32.7	30	8	10	17	22	30	30	0
3	12	„	4.3	12.9	18.8	30	10	13	18	20	29	30	1
4	15	„	5.2	15.5	46.6	30	6	13	19	22	29	30	1
5	18	„	6.0	21.0	52.6	30	8	13	18	24	29	30	4

(6) *Cyprinus carpio* [C]. Temperature of water=17.6~18.3°C.

No.	b	l	$V_{1,2}$	$V_{3,4}$	$V_{5,6}$	$V_{7,8}$	N	N_1	N_2	N_3	N_4	N_5	.....	Dead
			volt	volt	volt	volt								
1	6cm	20cm	2.1	4.2	8.3	16.6	30	9	11	12	15	19	.....	0
2	9	30	3.2	6.3	12.5	25.0	30	7	11	14	20	23	.....	0
3	12	40	4.2	8.3	16.7		30	7	10	17	19	22	.....	0
4	15	50	5.2	10.3	20.8		30	8	10	12	16	27	.....	0
5	18	60	6.2	12.4	(21.3/30cm)		30	8	10	14	23	(30)	.....	0

of fishes caused by the increasing of b was not observed because the length of the conduit was too short to contain the whole extension of the system of electrodes when l became larg, and we had to omit the stronger part of the field of electric current. For the same reason, among the curves of r_i in Fig. 3 (6), only those in which $i \leqq 4$ are to be discussed.

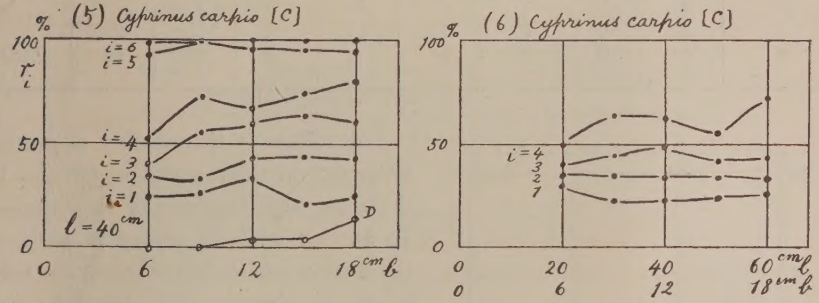

Fig. 3.

3. Distribution of the *turning points* between two consecutive electrodes: In the case given in Tab. I. (6), the *turning points* were most carefully observed and sketched as exact as possible, so that the distribution of *turning points* between two consecutive electrodes could be studied. In a sketch of the field of electric current such as shown in Fig. 4., each equal space between two consecutive electrodes was conventionally divided into equal number of sections having the breath of 10cm. Suppose Nos. 1, 2, etc. as having been put in every corresponding sections of thus divided spaces (Fig. 4). The numbers of *turning points* in all sections having the same No. were summed up, and the percentages of the number of each sums were calculated. The result is given in Tab. II and graphically in Fig. 5. From Fig. 5. it will appear that when l is larger than 40cm the *turning points* become very rare in the middle part between two electrodes; and that the *turning points* are most abundant in the section No. 1, *i. e.* just behind each electrode.

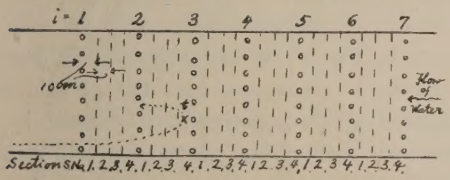

Fig. 4.

Table II.

No.	l	b	N	No. 1 0–10cm	No. 2 10–20cm	No. 3 20–30cm	No. 4 30–40cm	No. 5 40–50cm	No. 6 50–60cm
	cm	cm							
1	20	6	17	62%	38%				
2	30	9	30	40	33	27%			
3	40	12	27	56	10	9	25%		
4	50	15	27	37	15	7	15	26%	
5	60	18	23	26	4	4	22	22	22%

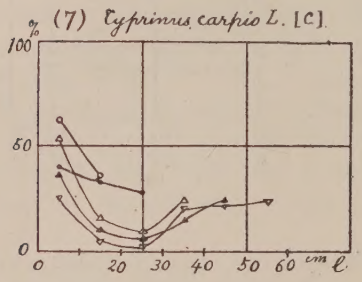

Fig. 5.

4. Rate of the number of groups prevented in their curse in relation to the speed and the size of the groups: In another series of tests, the speed of the groups just before entering the field of electric current was observed. According to the speed, the groups were divided into 3 classes: slow (5.3～8cm/sec), moderate (8～11.4cm/sec), and fast (11.4～23.3cm/sec). The rate of number of groups prevented in their course was calculated for each class, and its relation to the intensity of field of electric current was obtained as shown in Fig. 6, (8). The same data were treated in another way, where the groups were divided into three classes according to the size of the groups, *i. e.* the number of individual fishes composing a group, which was between 1～3, 4～10, or 11～30 respectively. For those three classes, the relation between the rate of number of groups prevented in their course and the intensity of field of electric current will be seen in Fig. 6, (9). From the result shown in Fig. 6, the following conclusions can be deduced. The slower the fish-group is swimming into the electric field, and the greater the number of individuals in a group is, the lower is the necessary intensity of electric current to prevent the movement of a definite percentage of the groups.

Discussion. The effect of electric current to prevent the movement of a fish-group may be a very complicated function of various factors. But it may chiefly depend on the mean value of the magnitude of excitation $\bar{E}$, due to electric shock on the individuals which are leading the movement of the

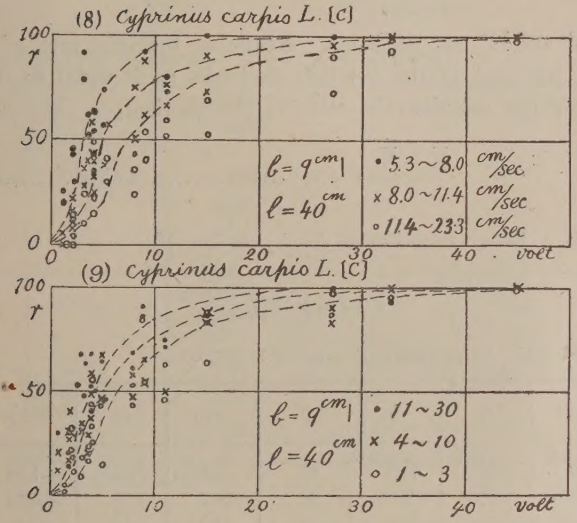

Fig. 6.

group. They may be called the leaders. There will be a definite value, E_e, of $\bar{E}$, which is just sufficient to turn a group back when the leaders are between ith and $(i+1)$th electrodes. Now, since E_e is subject to variation as the group differs, the probability that the leaders of a group turn back at any point in front of the $(i+1)$th electrode must be given by the following expression:

$$f(\bar{E}_i)=\frac{1}{\sqrt{2\pi}\sigma}\int_0^{\bar{E}_i} e^{-\frac{1}{2}\left(\frac{E_e-\bar{E}_e}{\sigma}\right)^2} dE_e, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where $\bar{E}_e$ is the mean value and σ the standard variation of E_e among different groups, while $\bar{E}_i$ is the value of $\bar{E}$ due to the field of electric current between ith and $(i+1)$th electrodes, of which the intensity is given by v_i or V_i.

Now if in each individual the relation between the excitation, E_i, and the intensity of electric current, v_i or V_i, follows after Weber-Fechner's law of excitation and stimuli, the relation between $\bar{E}_i$ and v_i or V_i must be given in the form:—

$$\overline{E_i}=a \log \frac{v_i}{v_o}, \text{ or } \overline{E_i}=A \log \frac{V_i}{V_o},$$

where a, v_o, A and V_o are constants. Assuming that the rate of number of *turning points* in front of the $(i+1)$th electrode, r_i, is equal to $f(\overline{E_i})$ in the equation (1), we can calculate the value of the quotient,

$$\frac{\overline{E_i}-\overline{E_e}}{\sigma}=\varphi(r_i), \quad \text{(2)}$$

which must be a linear function of $log\ v_i$ or $log\ V_i$.

TABLE III.

Cypsinus carpio [A]. Temperature of water=9.7~13.2°C.

No.	$V_{1,2}$	v_1	v_2	N	r_1	r_2	$\varphi(r_1)$	$\varphi(r_2)$
	volt	volt/cm	volt/cm					
1	2.0	0.031	0.051	31	6.5%	32.3%	−1.54	−0.46
2	3.75	0.059	0.095	30	26.7	36.7	−0.64	−0.34
3	6.25	0.098	0.158	31	58.0	77.4	0.20	0.78
4	8.75	0.137	0.222	38	60.5	92.0	0.26	1.42
5	10.0	0.156	0.253	36	69.3	94.3	0.52	1.60
6	20.0	0.312	0.510	19	89.5	90.0	1.28	1.30

In the most simple case, Fig. 1, (1), the relation between $\varphi(r_i)$ and $logv_i$ is found as shown in Tab. III and Fig. 7. In Fig. 7, this relation is rectilinear as it has been expected. Similar though not decidedly rectilinear relations are obtained in all other cases.

In the more complicated case, such as shown in Fig. 2, (2)~(4), the shifting between the curves of different tests seems to

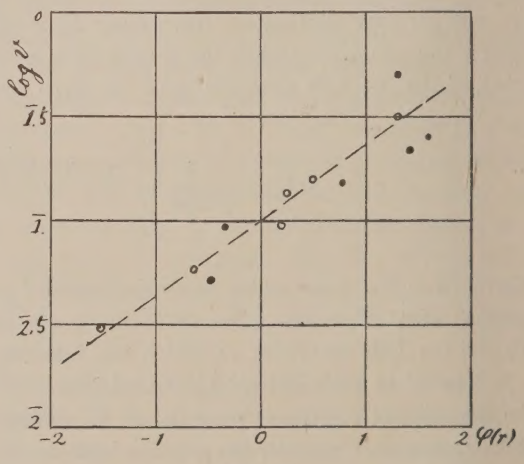

Fig. 7.

Table IV. ($b=9^{cm}$, $l=40^{cm}$)

Cyprinus carpio [C]. Temperature of water = 18.5~19.9°C.

Speed of group	Average speed	Total No. of groups	V_0	V_{50}	V_{100}
25~11.4 cm/sec	13.3 cm/sec	82	0.57 volt	7.4 volt	95 volt
11.4~ 8.0	9.2	128	0.33	5.1	79
8.0~ 6.6	6.7	87	0.48	3.2	21
Size of group	**Average size**	**Total No. of groups**	V_0	V_{50}	V_{100}
11~30	17.5	125	0.32 volt	4.5 volt	65 volt
4~10	5.1	156	0.30	5.1	78
1~ 3	1.9	169	0.38	6.5	111

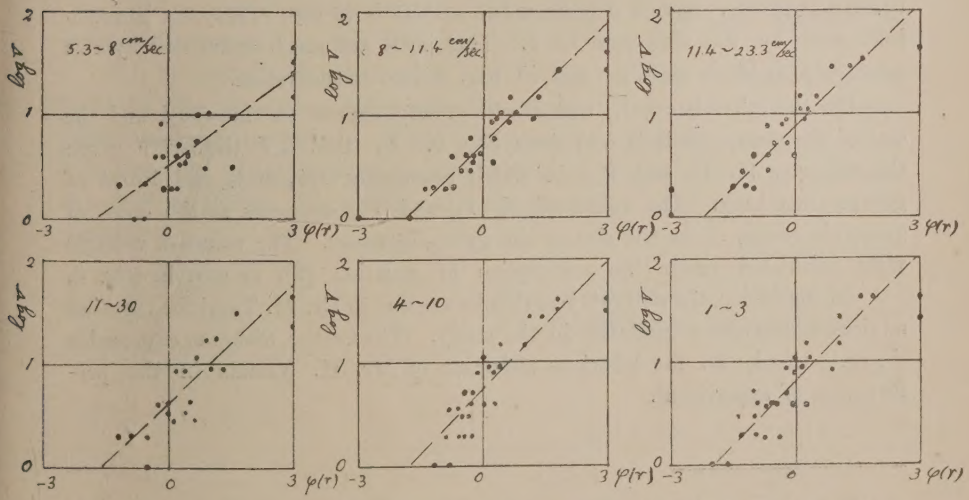

Fig. 8.

be explained, if we assume that too strong electrodes will prevent not only the movement of a group going up stream, but also that turning back,—an effect which was occassionally observed during the experiment. In fact, the result in Fig. 2, (2)~(4) tells us that a stronger field in an assigned ith space, has the tendency to be comparatively limited in the efficiency more than a weaker one. The fact that the *turning points* are most abundant in the neighbourhood of electrodes will support this view. But the great shifting, such as shown in Fig. 2, (4), can also result from the fact that, when the fore-part of the field of electric current is strong, only those fish-groups whose E_e is great can enter the strong field, and that in such a case $\frac{N_i}{N}$ does not properly represent the probability, $f(\overline{E}_i)$, as considered above.(1)

The value of constants, $\overline{E}_e$ and σ, in the equation (1) will depend not only upon the kind of fishes but also on the configuration of stream lines of electric current as well as on the speed and size of fish-groups, etc. In the cases shown in Fig. 3, the configuration of stream lines near the electrodes is similar when v_i is same, and it will equally be difficult for a group to pass through the electrode in all cases in consequence of the same geometrical probability for a group to encounter the part where the intensity of current is greater than a definite value. That is to say, r_i may not be much influenced by the difference in b. That r_i is not much influenced by l is most natural if we take the fact in Fig. 5 into consideration.

On the other hand, $\overline{E}_e$ and σ will greatly depend on the speed and the size of the group, as it is seen from Fig. 5. In Tab. IV there are given the voltages, V_0, V_{50} and V_{100}, in which practically 0%, 50% and 100% of groups turn back. The values of V_0, V_{50} and V_{100} decreases as the speed of group decreases, or as the size of the group increases. The values of voltages were calculated under the assumption of equation (2), as seen in Fig. 8.

In conclusion, the author's best thanks are due to Dr. M. Tauti for the kind advices and constant guidance in the study. The author wishes to express his sincerest thanks for the laborious assistance of Mr. H. Yasuda in the performance of experiment.

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(1) In the result shown in Fig. 2, (1), the number of *turning points* in front of the frontest electrode was taken into account. In other cases, such *turning points* were omitted because it was very doubtful whether the fish-group felt the current or not.

Summary.

1. Let r be the probability for a fish-group to be prevented in its course upstream by a part of field of electric current between two parallel net-formed electrodes. Then the general relation between r and the intensity of the field, v, can be expressed in the following equation:

$$r = \frac{1}{\sqrt{2\pi}\sigma} \int_{o}^{A \log \frac{v}{v_o}} e^{-\frac{1}{2}\left(\frac{x-x_o}{\sigma}\right)^2} dx, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where A, v_o, x_o and σ are constants.

2. Strong field of electric current has a tendency to be occasionally limited in the efficiency in suspending the movement of fish-groups, as compared with the efficiency expected from the general equation (1).

3. So far as the present study is concerned, the values of constants, x_o and σ, in the equation (1) are not much influenced by the difference in spacing between two electrodes, l, or that in the breadth of meshes of electrodes, b.

4. The neighbourhood of electrodes, especially the part just behind them, is most effective to turn the fish-group back.

5. The values of constants, x_o and σ, are seriously influenced by the speed of the fish-group going up stream or by the number of indvidual fishes composing the group. When the group is swimming slowly or when it is composed of many fishes, a weaker field of electric current can prevent the same percentage of a number of such groups, as a stronger one can do otherwise.

June, 1929.

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Anaesthesia of the Water-flea, *Moina macrocopa* Strauss, in Relation to Age.

By

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Monoclonal parthenogenetic females of the water-flea, *Moina macrocopa*, were kept in a jar in a compartment of Senô-Tauti serial incubator running at 27°C. Time required for anaesthetising them in a $\frac{N}{50}$ solution of chloretone warmed at 27°C was read to $\frac{1}{5}$ second with aid of stop-watches. The length of the water-flea, *i. e.*, distance between the head end and the posterior margin of the carapace, was measured under the microscope. The results are tabulated as follows:—

TABLE 1.

Age, length, and time required for anaesthetising the water-flea, *Moina macrocopa* Strauss.

Age in days	Number of individuals	Time required for anaesthesia in seconds			Length in millimeters		
		Mean	Standard deviation	Coefficient of variation	Mean	Standard deviation	Coefficient of variation
0	30	64.67± 1.03	8.33±0.73	12.88±1.14	.5300±.0653	.0435±.0038	8.21±.72
1	25	205.00± 3.41	25.30±2.41	12.34±1.20	.8970±.1210	.0402±.0038	4.48±.43
2	26	306.15± 3.57	27.01±2.53	8.82± .83	1.0365±.1371	.0288±.0027	2.78±.26
3	25	342.80±10.73	79.57±7.59	23.21±2.33	1.1630±.1569	.0382±.0036	3.28±.31
4	25	275.00±11.84	87.77±8.37	31.92±3.91	1.1890±.1604	.0301±.0029	2.53±.24
5	25	269.80±13.19	97.74±9.32	36.47±3.91	1.1910±.1607	.0809±.0077	6.80±.65
6	25	418.40± 9.56	70.86±6.76	16.94±1.66	1.2850±.1733	.0367±.0035	2.86±.27
7	25	476.60±12.20	90.41±8.62	18.97±1.85	1.4810±.1998	.0516±.0049	3.48±.33
8	25	483.00±10.98	81.39±7.76	16.85±1.65	1.3730±.1852	.0360±.0034	2.62±.25
9	24	360.00±13.65	99.12±9.65	27.53±2.88	1.3646±.1879	.0816±.0079	5.98±.58
10	27	390.74± 7.01	54.02±4.04	13.83±1.11	1.3898±.1804	.0299±.0027	2.15±.20

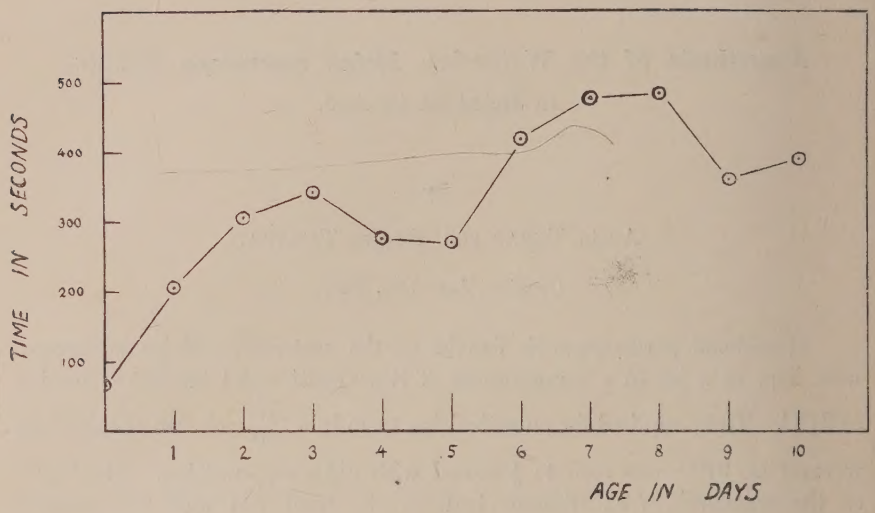

Fig. 1.

Showing the relation between time (in seconds) for anaesthetising the water-flea, *Moina macrocopa*, and age of the water-flea (in days).

It is clear that there are two drops in time required for anaesthetising the water-fleas although the lengths of the animals which are 4 and 9 days old are nearly the same as those of the animals which are respectively just one day younger than they are. Probably this fact is due to differences in vitality according to age of the experimental animals concerned.